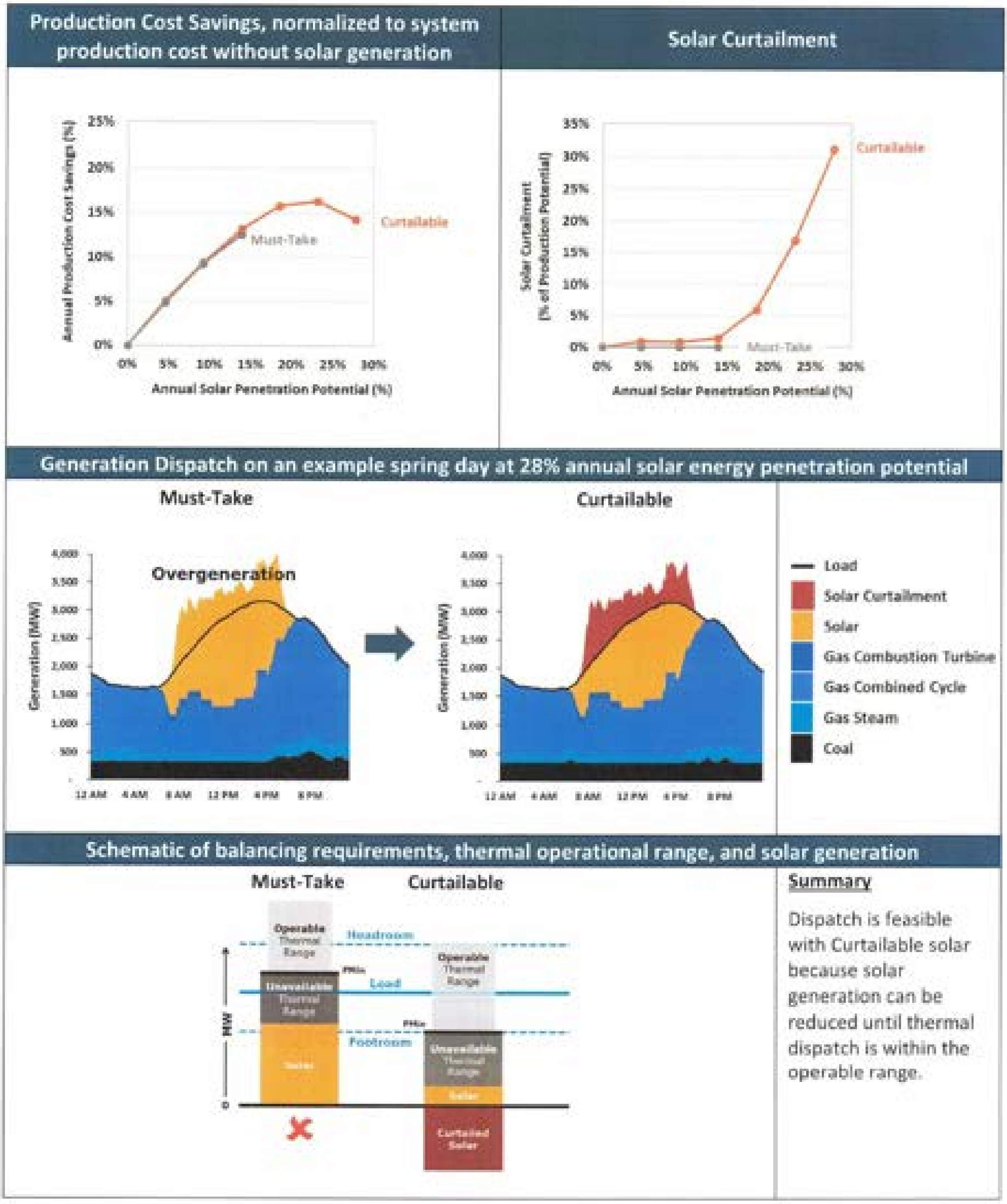
Figure 6: Summary: "Curtailable" Operating Mode

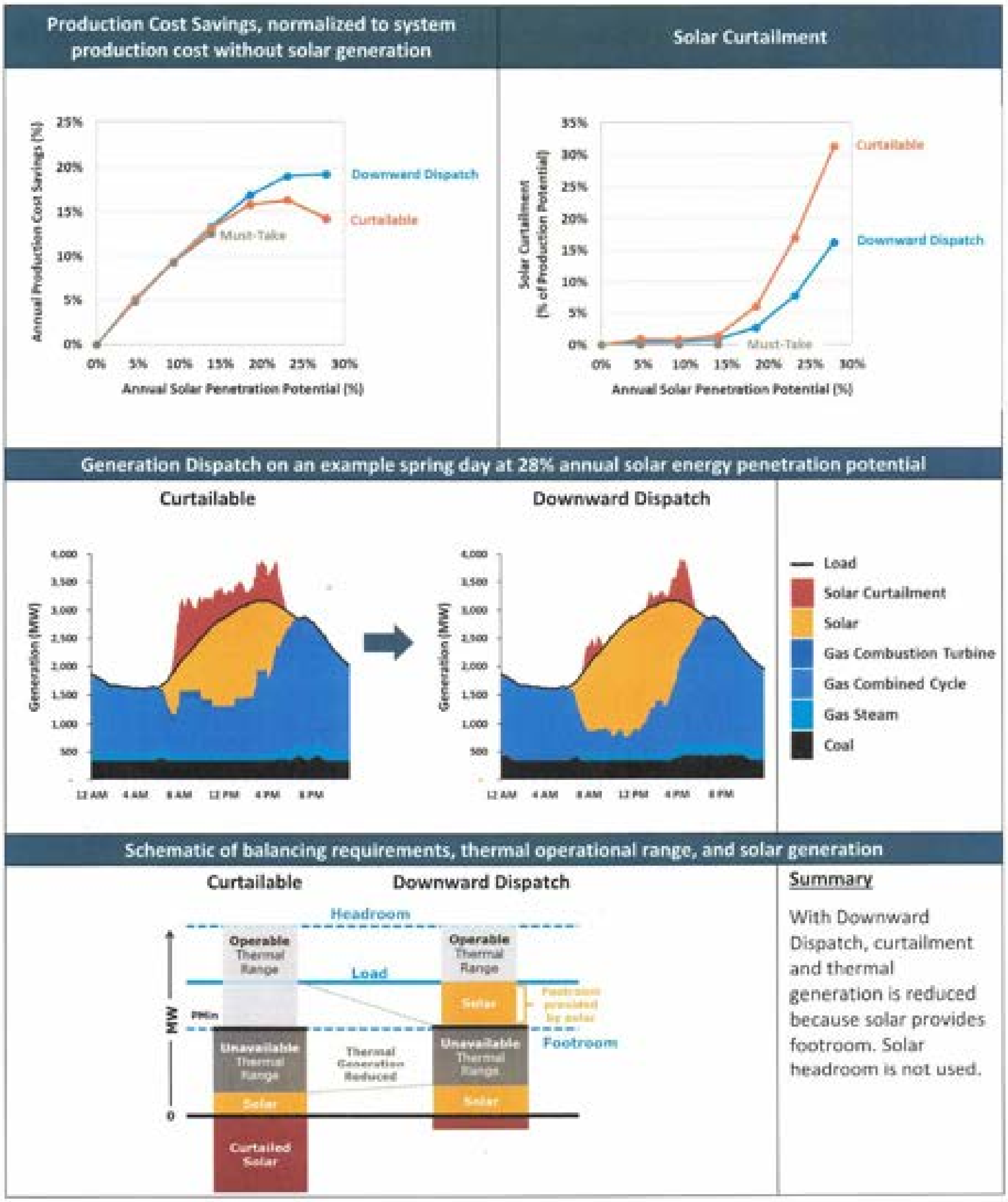


3.3 "Downward Dispatch" operating mode: Reduced curtailment and thermal commitment, and increased value

Compared to Curtailable operating mode, Downward Dispatch operating mode allows solar to retain value at higher levels of solar generation (Figure 7, top panel). Downward Dispatch improves on Curtailable by allowing the system operator to plan to turn down solar generation if solar is over-forecasted ahead of real-time operations. Downward Dispatch also allows regulation footroom requirements to be provided by solar generators. The middle and bottom panels of Figure 7 demonstrate that, during hours of very high solar output, downward dispatch of solar enables the operator to commit fewer thermal power plants, which reduces the minimum output requirement for thermal generation and increases the quantity of solar delivered to the grid. It may seem paradoxical, but in our simulations, solar in Downward Dispatch operating mode has *more opportunities* to be curtailed, but *less actual curtailment* is observed.[7] At 28% solar penetration potential, Downward Dispatch would reduce expected curtailment by half – from 31%, in Curtailable operating mode, to 16% – enabling solar to provide positive incremental value at higher solar penetration levels. Our simulation results show that, with the right economic dispatch rules, solar curtailment can be minimized by allowing solar to provide the most constrained grid services at key times.

[7] We do not estimate the amount of regulation that would be dispatched by AGC below the 5-minute timescale, and the resultant differences in energy production from AGC dispatch. In the Downward Dispatch and the Full Flexibility operating modes, we develop rules by which the system operator can rely on solar to provide downward regulation, but we do not assess whether it would be most economical to turn down solar or other resources in response to an AGC signal. In some instances, it may be more economical to turn thermal generation down instead of solar, thereby avoiding fuel costs.

Figure 7: Summary: "Downward Dispatch" Operating Mode



3.4 "Full Flexibility" operating mode: Additional value at higher solar penetrations

Sharing balancing requirements between thermal and solar generators becomes increasingly valuable as more solar capacity is added to the grid. Provision of balancing services from solar plants allows thermal generators to operate more efficiently by reducing the need for cycling and load following services, resulting in less fuel consumption. This also avoids commitment of inefficient thermal generation, reducing curtailment of solar during times of overgeneration.

Figure 8 shows that these savings can be substantial for the TECO system. The curtailment observed in Downward Dispatch operating mode on an example spring day (Figure 8, middle panel) suggests that at higher solar penetration levels, it could be particularly challenging to ramp TECO's thermal generation fleet down at sunrise and up at sunset. Operating solar in Full Flexibility operating mode would allow system operators to reduce forecast error headroom requirements and use any available solar headroom to meet regulation headroom requirements. On this example day, integrating these capabilities into operational procedures makes thermal generator ramping at sunrise and sunset more manageable.

Figure 8: Summary: "Full Flexibility" Operating Mode

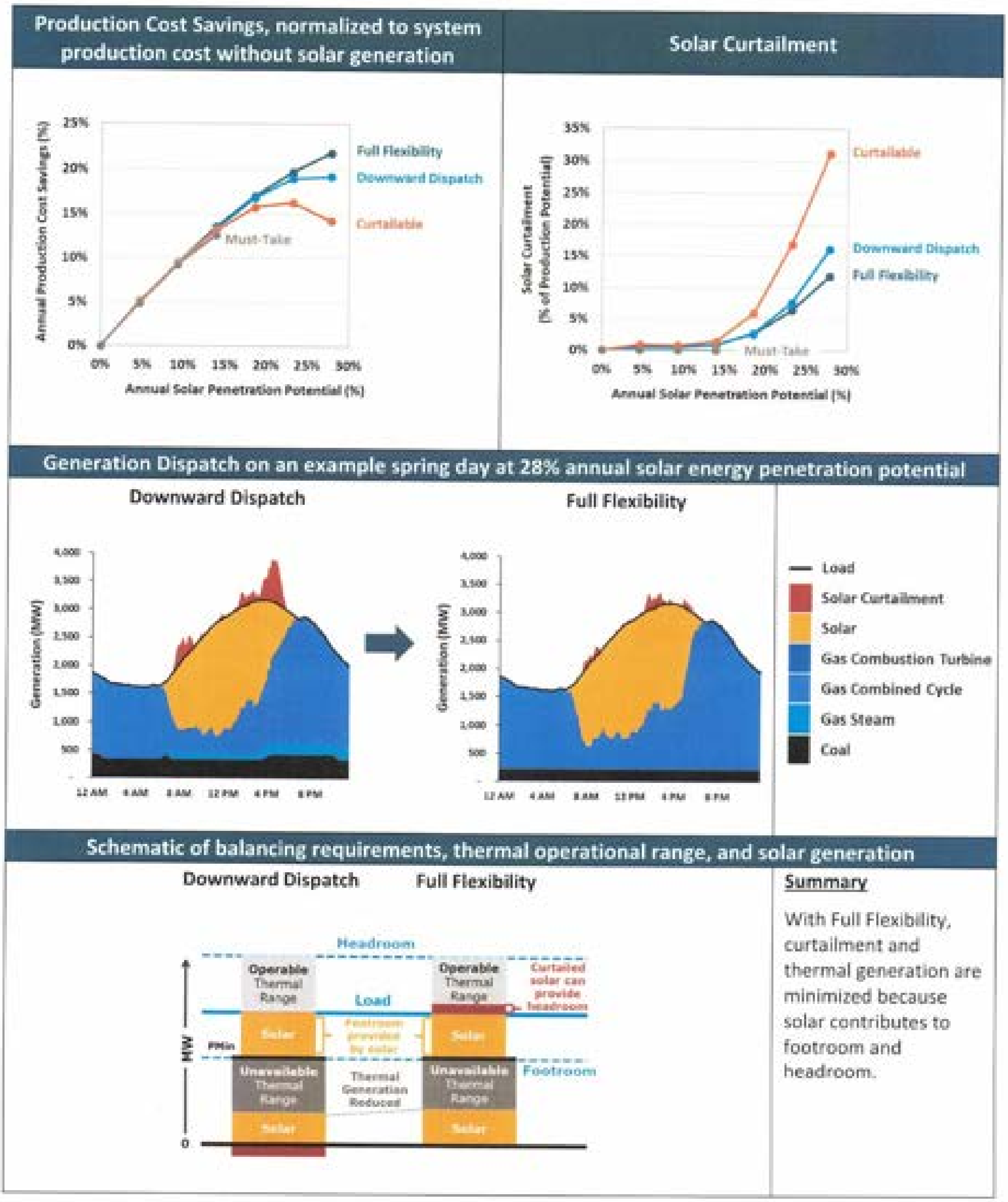
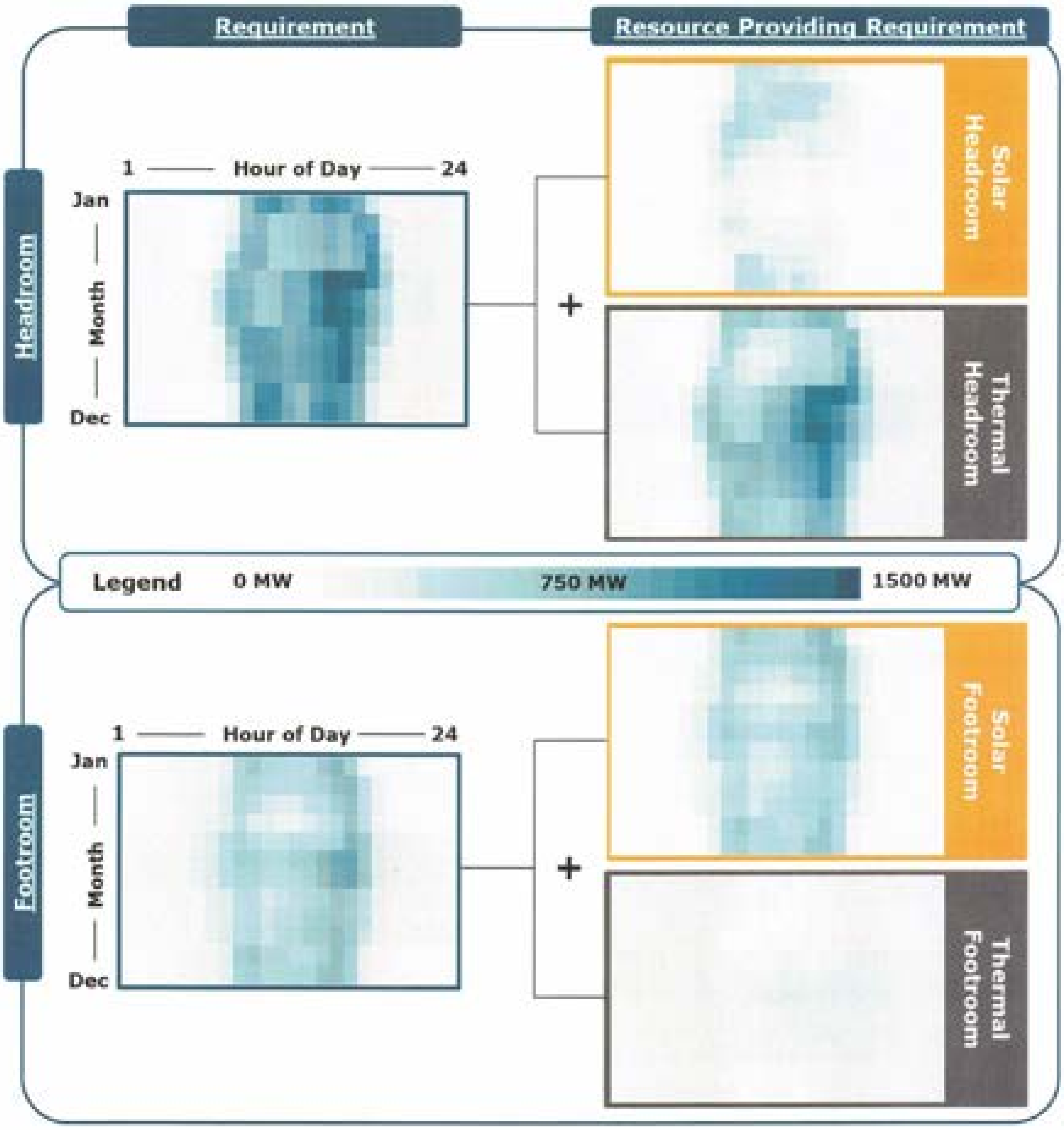


Figure 9 shows the distribution of headroom requirements between thermal and solar resources for the hours-ahead unit commitment stage. Footroom requirements during the daytime are met predominantly by solar.[8] Solar provides headroom to mitigate forecast uncertainties via committing to curtail and by committing to provide regulation. For example, solar is curtailed frequently in spring morning and early afternoon hours, thereby creating headroom that could be used productively to meet operational requirements. During summer late afternoon and early evening hours, solar does not typically reduce headroom requirements by committing to curtail because load is high enough in these hours to absorb (not curtail) most solar generation, and the TECO generation fleet has enough headroom flexibility to absorb all solar generation. Our results confirm that headroom on solar is most likely to be available during periods of low load and high solar output, but that solar generators are unlikely to be curtailed for the purpose of creating headroom during higher-load hours.

The scope of this study is limited to the operation of resources within TECO balancing area, and consequently transactions with external entities are not represented in detail. Energy market transactions with neighboring regions may become more valuable and/or frequent at higher solar penetrations. These transactions would allow TECO to access the capabilities of a larger pool of thermal resources, thereby making it easier to meet headroom, footroom, and ramping requirements. Forecast error headroom requirements may be particularly impacted by increased regional coordination, because the aggregate forecast error of a larger footprint of solar resources will be reduced relative to the same capacity of solar resources deployed over a smaller footprint. Increasing the level of regional coordination would reduce flexibility challenges related to adding solar resources into TECO's generation portfolio, thereby allowing solar energy to retain value at higher solar penetration levels. We expect that for a given level of solar generation, increased regional coordination would decrease the value of operating solar power plants in a more flexible manner. However, higher value for solar energy may hasten the pace of solar development across the region, thereby increasing solar penetration and consequently the value of solar flexibility.

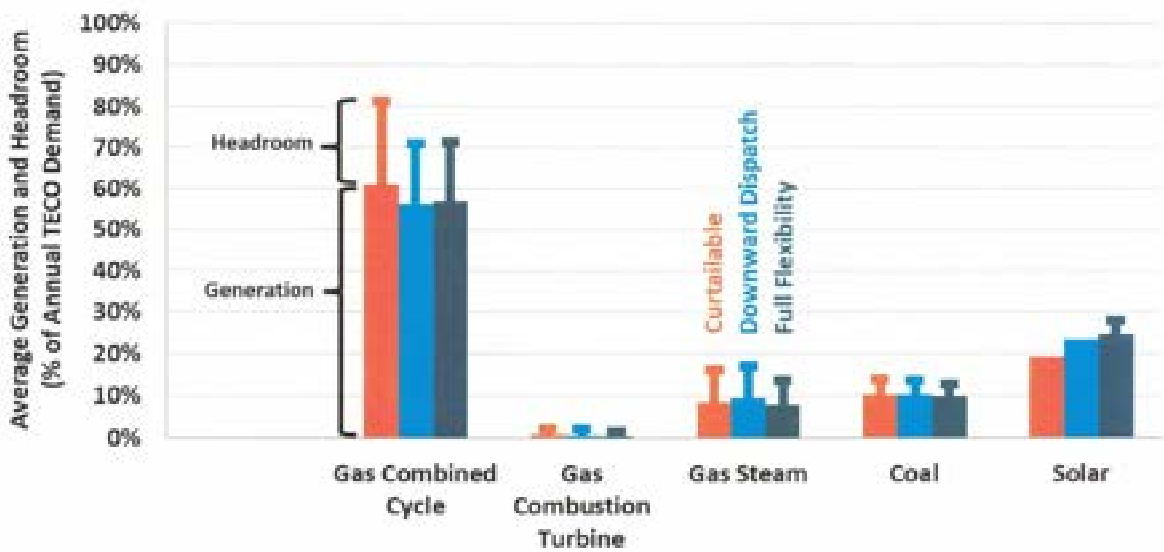
[8] When simulating the Downward Dispatch and Full Flexibility operating modes in PLEXOS, footroom requirements resulting from solar variability and uncertainty are not explicitly modeled because it is assumed that solar can provide these requirements if necessary. Simulation results do not show significant overgeneration events in real-time, confirming that footroom on solar for forecast error and within-hour variability is an effective balancing strategy. Our modeling does not simulate the dispatch of solar footroom held on AGC for balancing below the 5-minute timescale, but we expect solar to be effective on this timescale as well given the demonstrated capabilities of flexible solar plants.

Figure 9: Headroom and footroom requirements (left) and the portion of each requirement provided by solar and thermal resources (right) for the hours-ahead unit commitment stage at 28% annual solar energy production potential (2400 MW nameplate solar capacity) in the Full Flexibility operating mode. Values are month-hour averages.



Comparing thermal headroom and generation between the Curtailable and Full Flexibility operating modes (Figure 10, orange vs. dark blue bars) demonstrates that increasing solar flexibility reduces both thermal commitments and generation. The Curtailable, Downward Dispatch, and Full Flexibility simulations in Figure 10 have identical generator capacities and operational characteristics, except for their levels of solar flexibility. Note that no additional large capital investments would be necessary to reduce thermal capacity factors and commitment levels; increasing solar flexibility simply uses existing assets more efficiently, resulting in lower production costs.

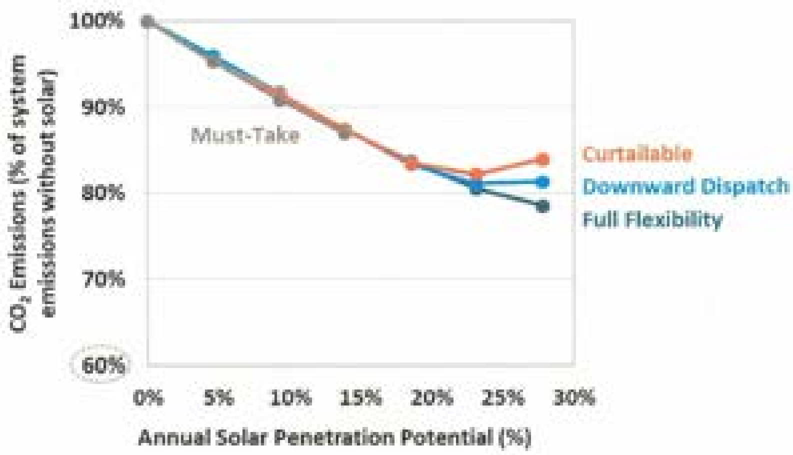
Figure 10: Annual average generation and headroom at 28% annual solar energy production potential, expressed as a fraction of annual TECO demand. Headroom is calculated as the difference between generation setpoint and committed capacity (or available production for solar) in real-time. Headroom on solar is only shown for the Full Flexibility operating mode.



3.5 CO_2 emissions results

Operating solar power plants in a more flexible manner enhances the ability of solar to reduce CO_2 emissions from electricity generation. As solar capacity increases, CO_2 emissions are reduced in all cases when solar is operated in Full Flexibility operating mode (Figure 11). At higher solar penetrations, Curtailable and Downward Dispatch operating modes result in more curtailment and higher levels of CO_2 emissions relative to Full Flexibility. At lower levels of solar penetration (less than ~19% annual solar penetration potential), we observe small differences in CO_2 emissions among the solar operating modes but do not believe them to be material.

Figure 11: CO_2 emissions as a function of solar deployment and solar operating mode



Flexibly scheduling and controlling solar plants can provide significant reliability, financial, and environmental value. Solar dispatch flexibility an important tool that grid operators can use to address challenges associated with higher solar penetrations and to integrate increasing amounts of solar cost-effectively. Dispatching solar power plants to the needs of the grid will reduce CO_2 emissions at higher solar penetrations and may reduce criteria pollutant emissions (such as NO_x), which can be significantly higher for power plants that frequently ramp up and down.

3.6 Summary tables

The numeric values in Table 3 and Table 4 indicate that increasing solar flexibility increases the value of solar energy and decreases solar curtailment. These values are for one specific system configuration, and depend on resource capabilities and capacity, fuel cost projections, and other many factors. Consequently, the values should not be applied to other jurisdictions or other TECO system conditions.

Table 3. Average and marginal energy value of solar, in $/MWh of solar production potential. The energy value of solar represents only production cost savings and does not include other value streams such as avoided peak capacity. The marginal energy value of solar is calculated as the change in production cost resulting from the addition of an incremental 400 MW of solar capacity.

Available Solar Generation			Average Energy Value of Solar ($/MWh)				Marginal Energy Value of Solar ($/MWh)			
Nameplate MW	Annual GWh	% of 2019 TECO Demand	Must-Take	Curtailable	Downward Dispatch	Full Flexibility	Must-Take	Curtailable	Downward Dispatch	Full Flexibility
400	958	4.6%	$28.7	$29.9	$30.1	$30.1	$28.7	$29.9	$30.1	$30.1
800	1,916	9.3%	$27.2	$27.5	$27.6	$27.8	$25.8	$25.1	$25.1	$25.5
1,200	2,874	13.9%	$24.6	$25.8	$26.1	$26.5	$19.5	$22.3	$23.2	$24.0
1,600	3,832	18.5%	N/A	$23.2	$24.7	$25.0	N/A	$15.5	$20.6	$20.5
2,000	4,790	23.2%	N/A	$19.2	$22.3	$23.2	N/A	$3.1	$12.8	$15.9
2,400	5,747	27.8%	N/A	$14.0	$18.9	$21.4	N/A	$ (12.1)	$1.4	$12.7

Table 4. Solar resource availability and solar curtailment results for each solar penetration level and operating mode.

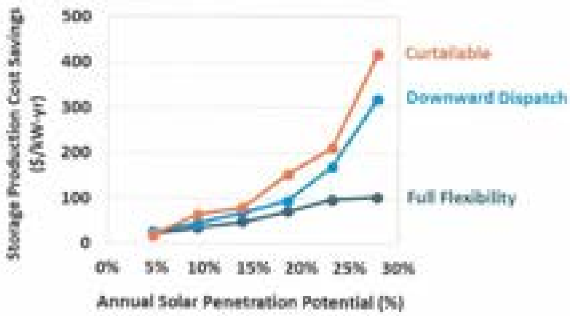
Available Solar Generation			Solar Curtailment (GWh)				Solar Curtailment (% of available solar energy)				Solar Penetration Achieved (% of 2019 TECO demand)			
Nameplate MW	Annual GWh	% of 2019 TECO Demand	Must-Take	Curtailable	Downward Dispatch	Full Flexibility	Must-Take	Curtailable	Downward Dispatch	Full Flexibility	Must-Take	Curtailable	Downward Dispatch	Full Flexibility
400	958	4.6%	0	8	5	5	0%	0.9%	0.5%	0.5%	4.6%	4.6%	4.6%	4.6%
800	1,916	9.3%	0	16	10	10	0%	0.8%	0.5%	0.5%	9.3%	9.2%	9.2%	9.2%
1,200	2,874	13.9%	0	41	24	26	0%	1.4%	0.8%	0.9%	13.9%	13.7%	13.8%	13.8%
1,600	3,832	18.5%	N/A	230	105	101	N/A	6.0%	2.7%	2.6%	N/A	17.4%	18.0%	18.0%
2,000	4,790	23.2%	N/A	811	370	311	N/A	16.9%	7.7%	6.5%	N/A	19.2%	21.4%	21.7%
2,400	5,747	27.8%	N/A	1,795	929	686	N/A	31.2%	16.2%	11.9%	N/A	19.1%	23.3%	24.5%

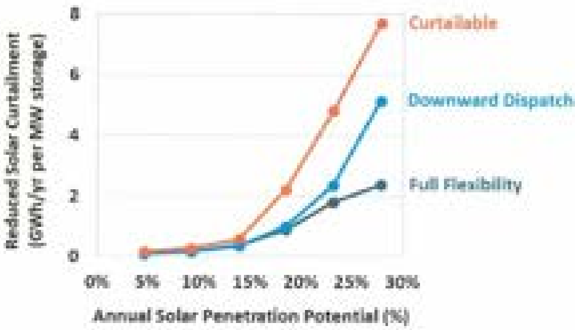
3.7 Sensitivity study: Incremental value of storage

Energy storage, particularly from fast-responding batteries such as lithium-ion, can quickly ramp from charging to discharge, providing an operating range that is double the nameplate capacity. Moreover, batteries can reduce fuel costs and avoid solar curtailment by charging during times of curtailment and discharging during times when thermal generation is on the margin.

For our final set of simulations, we add a small battery (50 MW, equivalent to ~1% of peak demand) with four hours of energy duration (200 MWh) to the TECO system at various levels of solar penetration to explore the value of storage in the context different solar operating modes. We find similar results to other storage production cost studies: storage provides production cost savings across all solar penetrations, with larger savings occurring at higher solar penetrations. Storage is used for a mix of regulation, forecast error reserves, and within-day energy shifting. Storage also reduces the magnitude of ramps during sunrise and sundown, which is more valuable at higher solar penetrations. The value of shifting energy increases significantly in the presence of solar curtailment (Figure 12). This study focuses on operational cost savings of storage, and therefore does not consider storage capital costs or a full cost-benefit analysis of storage.

Figure 12: Increasing solar operational flexibility can reduce the operational value of storage at a given solar penetration.





The opportunity for storage to add value is reduced when the system operator increases reliance on solar power plant flexibility, because flexible operation of solar can provide some of the same grid services as storage, especially footroom flexibility. Storage resources can be held in reserve ahead of real-time to address forecast errors in solar generation. The value of storage resources will be reduced if system operators can reduce forecast error footroom and headroom held on thermal generators by including solar curtailment in forecast error requirement calculations. In many renewable integration and storage valuation studies, a significant fraction of storage value comes from providing regulation. Solar resources could provide the same service during some portions of the day, potentially allowing the storage device to perform other functions. Also, solar curtailment decreases as solar operational flexibility is increased, thereby reducing the value of storage (see Figure 12) because fewer opportunities exist for energy shifting at a given solar penetration level. Renewable integration studies at higher renewable penetrations do not typically simulate wind or solar in the Full Flexibility operating mode, and therefore may overstate the value of storage. However, we recognize that if an electricity system already has a significant amount of storage or other flexible resources, the incremental value of increasing solar flexibility would be reduced relative to a system with less flexibility.

While our results suggest that increasing solar flexibility may reduce the need for storage (and/or other flexible resources) at intermediate solar penetrations, there is still a significant role for storage to play at high solar penetrations. As more and more solar is deployed in a grid, the operational value of adding energy storage will increase due to increased balancing requirements and increased solar curtailment. Storage can also provide significant system capacity value, whereas the marginal capacity contribution of solar resources tends to drop relatively quickly with increasing solar penetration.

4 Areas for Future Research

This study lays out some of the technical considerations that must be implemented to tap the full potential of flexible solar in grid operations. Further work is necessary on many fronts to fully realize the potential of flexible solar:

- Solar forecasts are key to unlocking the potential of flexible solar. Without some certainty on the possible bounds of power production, it is impossible to rely on a variable resource for balancing services, especially for services that require headroom. A method is needed to develop a confidence interval for flexible solar that is conservative enough to be workable in a control room while still providing a reasonable solar dispatch range. Providing footroom with solar requires significantly less forecast accuracy than is required to provide headroom.

- Disincentives for flexible solar exist in markets where Renewable Energy Certificates (RECs) are a primary revenue source, because RECs are only generated when the generator produces a MWh of renewable energy. A renewable power plant would not want to forgo REC revenue by offering to be dispatched unless doing so provided the generator with positive net revenue. Further research can shed light on the value of solar dispatch in a market with RECs.

- Many existing renewable power plants have contracts that do not envision using the plant for grid balancing, so contracts would need to be clarified or renegotiated to enable dispatchability from existing facilities.

- In organized electricity markets, it remains to be seen how variable renewables would bid their flexibility into energy and ancillary service markets. Existing methods of calculating opportunity cost for ancillary services are largely based on thermal opportunity cost of producing less energy and dispatching at less efficient setpoints. Compared to thermal generators, variable renewables have more uncertainty surrounding day-ahead or hour-ahead maximum production levels. Also, variable renewables may have no marginal cost of providing ancillary services if they are already curtailed due to system-wide conditions.

- Some organized markets do not separately procure upward (headroom) and downward (footroom) services. However, our study indicates that the cost for solar to provide headroom and footroom is highly asymmetric. Flexible solar is likely to have significantly higher value in markets, like the California ISO, with distinct upward and downward reserve products. Other market operators in areas with high wind and solar penetration should consider establishing separate downward and upward reserve products.

5 Conclusions

When envisioning a power system with large amounts of variable renewable energy, system planners must include information on the least-cost manner of reliably operating that system, in both the present and future. If system operators can control the power output of variable renewable resources, these resources can be viewed as assets that help to maintain reliability rather than liabilities that create operational challenges. Bringing the operational value of dispatching variable renewables into utility resource plans may change the investments made in resources going forward. The flexibility brought by dispatching variable renewable generators could reduce the need for investments in other types of flexible resources. But dispatching renewables helps to retain their value at higher penetrations, which may induce further renewable deployment and, in turn, increase the need for other flexible resources. In either scenario, reducing operational costs and CO_2 emissions from the power system is easier when solar power is treated as an active participant in grid balancing rather than an invisible part of the "net load."

6 Appendix A: Reserve Calculations and Requirements

Many renewable integration studies calculate headroom and footroom requirements such that unit commitment and dispatch decisions include enough flexibility to successfully navigate variability and uncertainty from load and variable renewable resources. Calculating reserve requirements is an active area of research, but at present most studies follow a similar calculation methodology.[9] In our study, we calculate reserve requirements largely using standard methods but make modifications necessitated by the multi-stage structure of our PLEXOS model and solar flexibility constraints.

We enforce three separate categories of reserve requirements in PLEXOS: forecast error (Section 6.1), regulation (Section 6.2), and contingency (Section 6.3). Section 6.4 describes how different classes of resources provide each category of reserves.

To calculate forecast error and regulation reserve requirements, we rely on year-long timeseries data for load and solar production. Both load and solar datasets include forecasted and real-time (5-minute actual) data. Solar timeseries data is described in Section 2.1.3. TECO provided a year-long timeseries of forecast and actual (5-minute) load data.

6.1 Forecast error reserves

Forecast error reserves ensure that enough capacity is committed before real-time such that load and solar forecast error do not cause reliability concerns. Both upward and downward requirements (headroom and footroom, respectively) are enforced in every model stage before real-time. Our

[9] E. Ibanez, I. Krad and E. Ela, "A Systematic Comparison of Operating Reserve Methodologies," National Renewable Energy Laboratory, 2014, https://www.nrel.gov/docs/fy14osti/61016.pdf; I. Krad, E. Ibanez and W. Gao, "A Comprehensive Comparison of Current Operating Reserve Methodologies," IEEE/PES Transmission and Distribution Conference and Exposition (T&D), 2016.

treatment of forecast error reserves is similar to "load following" or "flexibility" reserves in other renewable integration studies, with the exception that the within-hour variability traditionally associated with "load following" calculations is included as part of the regulation requirement in this study.

6.1.1 FORECAST ERROR REQUIREMENT CALCULATION

For each of the three model stages before real-time (i.e., multiple days-ahead, day-ahead, and hours-ahead), the difference between forecast and average actual output is calculated, resulting in a library of positive and negative MW forecast error values. The calculation is performed *individually* on demand and solar profiles. To capture correlations between demand and variable renewable resources, many studies in the literature subtract variable renewable output from demand to create a library of *net load* forecast error values. We do not employ this method because quantifying the level of solar forecast error is key to representing solar flexibility in the production simulation. At higher levels of solar penetration, we observe that solar forecast error is much larger than demand forecast error, which minimizes the difference between individual and net load forecast error calculation methodologies. In future analyses, it may be possible to retain correlations between solar and demand forecast errors when modeling solar flexibility.

To reflect different levels of forecast error at different times of the day, the library of forecast errors is divided into bins by hour of day. Because TECO experiences different weather conditions during different times of year, the hourly bins for solar forecast error are subdivided by season. Finally, to reflect differences in forecast accuracy resulting from cloud cover, the season-hour bins are divided into two separate bins: "cloudy" and "clear sky." Solar forecasts are placed into the "cloudy" bin if the forecasted solar output is less than 80% of an estimate of the clear sky output.

System operators make conservative decisions when committing generation units, but it is not common practice to commit units to prepare the system for *every* possible future level of load or solar production. In the case of extreme forecast error, operators can perform a set of emergency actions that fall outside of the scope of production cost modeling, such as making an emergency phone call to a neighboring balancing area, dispatching contingency reserves, or allowing a small imbalance in supply and demand (thereby causing area control error) for a short period of time. Consequently, an appropriate threshold for forecast error reserves must be defined beyond which the system operator does not need to hold headroom or footroom for forecast error. This threshold can be the product of a detailed analysis that compares the value of a more reliable system with the incremental cost of holding more reserves. In many studies, a detailed cost/benefit analysis is not within scope so reserve requirement levels are selected by choosing a percentage of forecast errors based on prior studies of similar systems. Commonly used thresholds are either ~68 – 70% (roughly one standard deviation, 1σ, for a normally distributed set of forecast errors) or 95% (2σ), meaning that the unit commitment simulation will ensure that all but ~28 – 30% or 5% (respectively) of all possible forecast errors can be met by available resources.

To calculate forecast error reserves for solar in our study, we truncate the library of forecast errors to include 70% (~1σ) of all forecast errors when committing units ahead of real-time (i.e., the multiple days-ahead, day-ahead, and hours-ahead unit commitment stages). Doing so results in forecast error reserve requirements in both the upward (headroom) and downward (footroom) directions because both under- and over-forecast events are included in the timeseries datasets. We follow the same procedure for load forecast error, except that we expand the range of forecast errors that we included in the hours-ahead stage to include 95% (2σ) of all forecast errors. We truncate the library of forecast errors separately for load and solar, and then add the result to obtain the final reserve requirement.

The final step of the forecast error reserve calculation ensures that solar forecast error reserve levels remain within the bounds of possible solar production. Because solar production cannot go below zero, the forecast error headroom requirement is adjusted if the forecasted solar production minus the headroom requirement is less than zero. Because solar production cannot go above the level at which the power plant would produce under clear sky conditions, the forecast error footroom requirement is adjusted if the forecasted solar production plus the footroom requirement is greater than an estimate of the clear sky production potential for a given timestep.

Studies in the literature demonstrate that forecast error for a geographically diverse set of variable renewable resources is typically lower than forecast error for the same capacity of resources installed on a smaller footprint. For this study we assume that all solar deployment will occur within the TECO service territory, which is a relativity small portion of the Florida peninsula. Consequently, we do not reduce the marginal forecast error contribution of additional solar resources as more solar is added to the TECO system. If solar resources were to be deployed on a larger geographic footprint, forecast error requirements would be reduced and consequently the benefits of flexible solar operation would be lower at a given solar penetration. Similarly, improved solar forecasting would decrease the cost of solar integration, which would raise the value of solar facilities at any solar penetration and decrease the value of flexible solar operation at a given solar penetration.

6.2 Regulation reserves

Regulation reserves are held for short-timescale variation – less than 1 hour – of load and variable renewable output. In our study regulation reserves represent the amount of within-timestep variability that the system operator must manage if average load and solar production are perfectly forecasted at an hourly timestep for the multiple days and day-ahead unit commitment stages, a 15-minute timestep in the hours-ahead unit commitment stage, or a 5-minute timestep in the real-time unit commitment stage.

6.2.1 REGULATION RESERVE REQUIREMENT CALCULATION

We calculate regulation requirements on two different timescales (hourly to 5-minute and 5-minute to automatic generation control (AGC)) and add the result to obtain the final reserve requirement. Only the 5-minute to AGC component of the regulation requirement is held in real-time dispatch, because the real-time stage economically commits and dispatches on 5-minute intervals, thereby removing the need to hold additional headroom and footroom for variability between hourly and 5-minute commitment intervals. Regulation requirements for solar are calculated from a real-time 5-minute production profile that is the average of many individual production profiles from across the TECO region.

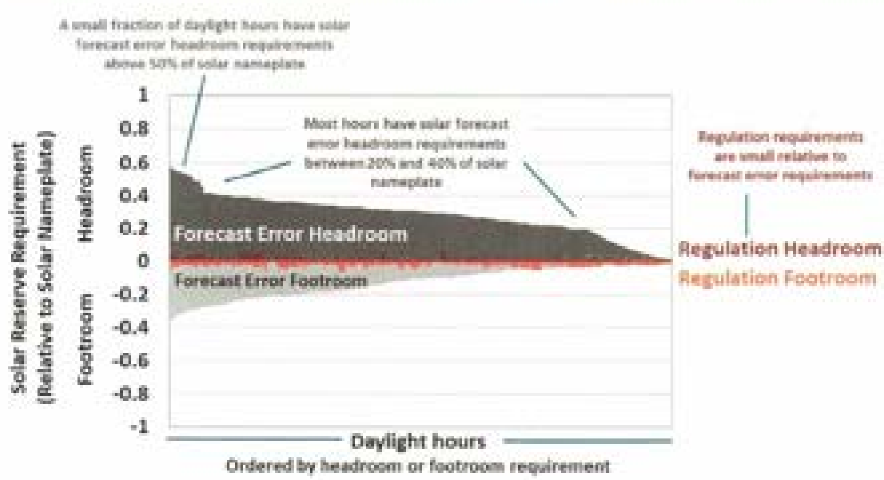
<u>Hourly to 5-minute timescale:</u> Real-time 5-minute load or solar production profiles are subtracted from a linear interpolation between hourly (multiple days-ahead and day-ahead) or 15-minute (hours-ahead) averages of the same real time profile. As with the forecast error calculation, this results in a library of positive and negative error values. Errors are divided into bins by hour of day for load, and by hour of day, season, and a cloudy/clear sky binary for solar. We calculate the hourly to 5-minute regulation requirement by truncating the library of errors within each bin to include 95% of errors.

5-minute to AGC timescale: To calculate the solar component of the AGC requirement, we estimate the short-term variation in plant output on a 5-minute timescale. We compare a cloud cover persistence forecast based on solar output in one 5-minute timestep to actual solar output in the next 5-minute timestep. Similar to other calculations, we bin the result by hour of day and season, and then apply a 95% error cutoff.

We calculate the 5-minute to AGC requirement for demand as 1% of demand, a value frequently used in other production simulations.

Figure 13 shows the combined regulation and forecast error headroom and footroom requirements for solar uncertainty and variability for the hours-ahead unit commitment stage. Only daylight hours are depicted in Figure 13. Forecast error requirements are typically much larger than regulation requirements. The relatively large magnitude of the forecast error headroom requirements is in part due to the small geographic scope of the TECO balancing area.

Figure 13: Solar reserve requirement duration curve for the hours-ahead unit commitment stage.



6.3 Contingency reserves

Contingency reserves are held for infrequent but extreme events, typically the loss of a large generation unit or transmission line. In our simulations, contingency reserves are held in all model stages, including real-time, because system operators must always be prepared for contingency events. Consistent with current operational practice, contingency reserves are only enforced in the upward (headroom) direction.

6.3.1 CONTINGENCY REQUIREMENT CALCULATION

Contingency reserve requirements for the TECO system were implemented with input from TECO staff. The magnitude of reserve need is calculated endogenously in PLEXOS for every time step as the maximum of:

- TECO's largest generation contingency
- TECO's share of the Florida reserve sharing obligation
- A minimum contingency reserve level of 315 MW

6.4 How resources provided reserves

Table 5. How different classes of resources provide headroom and footroom capacity to each reserve type.

Resource	Forecast error	Regulation	Contingency
Online thermal	Headroom and footroom*	Headroom and footroom, subject to ramp rate limits	Headroom, subject to ramp rate limits
Offline thermal	Nameplate capacity of generators that could start within the required timeframe, but combustion turbines in a combined cycle can only contribute if the steam turbine was committed	Could not contribute	Nameplate capacity of simple cycle combustion turbines that can start within the required timeframe
Batteries	Available headroom and footroom	Available headroom and footroom	Available headroom
Demand response	Does not contribute	Does not contribute	Available capacity
Solar	See Table 6 below		

*Online generators that can shut down with sufficient speed contribute capacity equal to their minimum production (PMin) to forecast error reserve footroom, in addition to available footroom between their setpoint and PMin.

Table 6. Schematic representing how solar generators provide reserves in this study.

	Reserve Type	Source of need	How does solar provide?	
Total Headroom / Headroom (MW)	Contingency	Largest contingency	Headroom on solar for contingency reserves is not modeled in this study, but would be possible with enough production potential certainty	
Headroom (MW)	Forecast Error + Regulation Headroom	Solar variability and uncertainty	Forecast error up from solar is reduced when solar is curtailed	When solar provides regulation headroom, more forecast error reserve is held in case of solar over-forecast
		Load variability and uncertainty	Headroom on solar for load under-forecast is not modeled in this study, but would be possible with enough production potential certainty	
Forecast Load / Footroom (MW)	Forecast Error + Regulation Footroom	Load variability and uncertainty	Solar provides footroom for load over-forecast, limited by the amount of solar generation below the lower bound on solar production	
Total Footroom		Solar variability and uncertainty	Reserve need is not modeled because solar can be curtailed in real time if energy cannot be absorbed	

7 Appendix B: Prior Research

Prior research that simulates solar (or wind) in Curtailable or Downward Dispatch operating mode includes the following:

- GE Energy, "Western Wind and Solar Integration Study," National Renewable Energy Laboratory, May 2010, https://www.nrel.gov/docs/fy10osti/47434.pdf.
- Mills, A., A. Botterud, J. Wu, Z. Zhou, B.-M. Hodge and M. Heaney, "Integrating Solar PV in Utility System Operations," Argonne National Laboratory, 2013, http://eta-publications.lbl.gov/sites/default/files/lbnl-6525e.pdf.
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